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DESIGN OF A LONG ISOTROPIC BUFFER ROD

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ABSTRACT

Considerations for the design of long isotropic buffer rods used in ultrasonic measurements are presented. The buffer rods of interest have diameters between a few to several tens of acoustic wavelengths, and lengths of more than a hundred acoustic wavelengths. Longitudinal and shear wave measurements obtained on aluminum rods with an ultrasonic pulse-echo system are presented and interpreted theoretically in terms of diffraction from the transducer and mode conversion at the walls of the buffer rod. A buffer rod with a tapered shape is found to have the best performance for longitudinal waves.

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1. INTRODUCTION

Ultrasonic pulse-echo techniques are in widespread use for the nondestructive evaluation (NDE) of materials. The main applications are the measurement of elastic properties such as ultrasonic velocity and attenuation, and the detection of discrete defects in the material under test. Very often measurements are required under difficult conditions such as elevated or low temperatures [1], high or low pressures [2], thus buffer rods are sometimes necessary to avoid exposing the ultrasonic transducer to such conditions. In general a buffer rod should have the following properties; (1) low acoustic attenuation and diffraction loss for longitudinal and/or shear wave propagation, (2) good acoustic impedance matching with the ultrasonic transducer and the material under test and (3) proper mechanical and thermal properties.

In most ultrasonic measurements employing a buffer rod, a test sample is attached to one end of the buffer rod and the echoes coming from the test sample are analyzed. One may use these echoes to deduce the ultrasonic velocities and attenuations [1,2]. However, some spurious signal may exist due to wave diffraction in the buffer rod. These echoes arrive later than the direct transmitted or reflected longitudinal or shear wave echoes and are unwanted because of the possible interference with the desired signals from the sample. The purpose of this paper is to describe and understand these late-arrived or trailing echoes and find methods of eliminating them.

Single crystals such as sapphire or quartz normally have very low loss, but are expensive and often have mechanical and thermal properties which are not compatible with measurement conditions. For instance, during the thermal cycles of a test, cracks may develope in the crystal. Furthermore, ultrasonic diffraction in single crystals is very complicated [3,4] especially for a rod geometry due to the anisotropy of the longitudinal and shear wave velocities. Therefore, in this paper only isotropic buffer rods are considered.

The rods of interest have a diameter between a few to tens, and lengths of more than a hundred acoustic wavelengths. Longitudinal and shear wave measurements performed on aluminum rods with an ultrasonic pulse-echo system are presented. Aluminum (Al) is chosen here because it can be easily machined to the desired testing geometries. In addition, Al has also reasonably low ultrasonic loss and good mechanical strength. The theoretical interpretation of the received signals in the experiments can be applied to other isotropic materials such as fused quartz rods. Based on the theoretical understanding described in this paper for trailing echoes in cylindrical rods a buffer rod with a tapered geometry was then designed and tested.

II. EXPERIMENTS

The pulse-echo electronic system consisted of a pulser and a broadband receiver from Metrotek (Richland, WA). The ultrasonic transducers were also broadband obtained from KB-Aerotech (Lewistown, Penn.) or Panametrics (Waltham, Mass.). The reasons for the selection of broadband transducers are (i) damped

transducer provides better time-delay measurement resolution and (ii) the frequency spectrum of the acoustic signals may reveal more information about the test sample. However, it is noted that highly damped transducers have less efficiency than lesser damped transducers. Since the buffer rod design for both longitudinal and shear wave propagation is of interest, they are discussed seperately below.

II.A Longitudinal Waves

Longitudinal acoustic wave measurements have been performed using aluminum (Al) rods with different diameters and lengths (see Fig.1) in the transmission or reflection geometry. A common commercial ultrasonic couplant was between the transducer and the Al rods. Table 1 gives the descriptions of several Al rods shown in Fig.1. Many transducers with different operating frequencies and apertures were also used. Here only representative results are given.

TABLE 1 Descriptions of Al Rods

Type	Diameter (mm)	Length (mm)	Remarks
A	7.95	222	uniform diameter
B	12.7	220	uniform diameter
C	19.0	219	uniform diameter
D	12.7 (inner) 19.0 (outer)	213	double spiral notches (notch depth 3.15 mm)
E	12.7 (end 1) 19.0 (end 2)	209	tapered rod

Figure 2 shows the reflected echoes through the Al rod 'B' (uniform diameter of 12.7 mm) using a 5 MHz KB-Aerotech transducer with a 12.7 mm diameter. The echo 'a' is the first longitudinal arrival. As mentioned in the previous section echoes 'b', 'c' etc arriving later than 'a' are called trailing echoes. These trailing echoes also appear in the transmission geometry. Echoes 'a', 'b' and 'c' for Al rods 'A', 'B' and 'C' (having diameters of 7.95, 12.7 and 19.0mm respectively) obtained in the reflection geometry are shown in Figs.3(a)-(c). The amplitudes in Figs.3(a)-(c) are arbitrary, but relatively the differences in the received maximum amplitude of echo 'a' for Al rods 'A' to 'C' using the above mentioned transducer are about -27, -6, 0 db respectively. From the results shown in Figs.3(a)-(c) and other experiments not reported in detail here [5] the following observations have been noticed:

(i) Time delays t_d's between 'a' and 'b', 'b' and 'c', 'c' and 'd' etc are nearly equal.

(ii) The time delay t_d is proportional to the rod diameter but independent of the length.

(iii) One narrow notch 4 mm deep around the entire circumference and placed at the center of the rod or off center does not affect the td.

The presence of trailing echoes was first reported in Ref.[6], but no attempt was made to evaluate t_d. In fact, the cause of the time delay t_d can be explained by a mode conversion process illustrated in Figs.4(a)&(b). The longitudinal waves travelling almost parallel to the rod-air interface but with a small angle

of inclination impinge on the interface and induce mode conversion from longitudinal (L) to shear waves (S). The roughness of the surface also enhances this conversion. It is noted that there are two shear waves with orthogonal particle polarizations in Fig.4(a), and because they are degenerate (i.e. having the same velocity), they are represented by a single curve [4,5]. The mode conversion is dictated by the phase matching requirements, hence the θ in Fig.4(a) is equal to $\sin^{-1}(v_s/v_l)$. v_s and v_l are the shear (3109 m/s) and longitudinal wave velocities (6420 m/s) of the Al respectively. The phase matching condition requires that the wavenumber components of the waves involved in the mode conversion along the interface must be equal [4], where wavenumber k is equal to $2\pi/\lambda = 2\pi f/v$. When the converted shear waves strike the other side of the rod-air interface, they are converted back to longitudial waves because the phase matching conditions still hold. This can be seen if the directions of the arrows in Fig.4(a) are reversed. Thus from propagation paths of echo 'a' and 'b' shown in Fig.4(b) t_d which is the arrival time delay difference between echoes 'a' and 'b' (or 'b' and 'c', etc) can be expressed as

$$t_d = \frac{d/\cos\theta}{v_s} - \frac{d*\tan\theta}{v_l} \qquad (1)$$

It is noted that t_d is proportional to the rod diameter, d, as observed experimentally. Using Eqn.(1) the calculated and the measured t_d between echoes 'a' and 'b' shown in Figs.3(a), (b) and (c) are 2.25 and 2.25, 3.67 and 3.60, 5.40 and 5.40 μs

respectively. The agreement is excellent. In addition, the echoes 'b' and 'c' etc are the sources of echoes 'c' and 'd' etc respectively, therefore the time differences between these trailing echoes are nearly the same. Since the mode conversion process occurs continuously along the rod, the presence of narrow notches or the length of the rod do not affect the time t_d. Thus the three obervations mentioned above have been explained consistently by the mode conversion process.

The trailing echoes 'b', 'c' etc are the result of wave diffraction in the rod. The ratio between the energy sum of all trailing echoes over that of the first arrived longitudinal echo 'a' may be used to evaluate the degree of diffraction in the rod. In order to reduce this ratio one obvious method is to increase the diameter or shorten the length of the rod. It is noted that the increase of the acoustic operating frequency can also reduce the diffraction effect [3], hence this ratio. another alternative is to disturb the rod-air boundaries as in the rod 'D' shown in Fig.1. Rod 'D' was made in a way that two spiral-like V grooves with a depth of 3.15 mm are surrounding the rod. The diameter of the untouched portion inside the rod 'D' is 12.7 mm, which is the same as that of rod 'B', and the outer diameter is 19.0 mm. The spiral directions are both clockwise and counter-clockwise so that no cylindrical symmetry can be found along the rod. A buffer rod with spiral grooves was used in the ultrasonic experiments in Ref.[1], but no detailed explanation was given. In Ref.[7] the equivalent acoustic impedance of periodic grooves with depth h is expressed as an imaginary quantity. In the case where h is equal

to half a wavelength, $\lambda/2$, then the magnitude of this imaginary impedance is very large. This means that in principle the periodic grooves will absorb the incoming waves with a frequency $f = v/\lambda$. The groove depth of 3.15 mm in rod 'D' was designed to eliminate the trailing echoes of the dominant low frequency components of our broadband system. The reduction of trailing echoes due to these grooves is clearly illustrated by comparing the reflected echoes through the Al rod 'B' in Figs.3(b) with those through the Al rod 'D' shown in Fig.5 using a 5 MHz KB-Aerotech transducer with a 12.7 mm diameter. The signal level of echo 'a' for rod 'D' is nearly the same as that for rod 'B'.

Another alternative to reduce the trailing echoes is to disturb the boundary such that the waves generated due to the mode conversion along the rod will not be added in phase at the receiver. Al rod 'E' having the tapered shape shown in Fig.1 was made based on this approach. The diameter of one end of the rod is 12.7 mm and that of the other end is 19 mm. Mode conversion still exists at the rod-air boundary along the Al rod, but the trailing echoes are negligible as seen from Fig.6. The signal level of echo 'a' for rod 'E' is nearly the same as that for rod 'B'. There is no observable difference in the received signals whether the ultrasonic transducer is located at the thin or wide end of the tapered Al rod. Comparing Figs.5 and 6 it is concluded that the rod 'E' having a tapered shape performs better than rod 'D' having a spiral boundary. If the slope of the tapered Al is increased, the amplitude of trailing echoes will further decrease. It is noted that if the transducer type is changed,

(e.g. Ultran 5 MHz transducer from Ultran, State College, Penn. to replace Kb-Aerotech 5 MHz transducer), the shapes and the amplitudes of trailing echoes will also change because of the effects upon diffraction [8] of the input particle velocity profile across the tranducer. But the time delays t_d in rods 'A', 'B' and 'C' and the degrees of the improvement of the reduction of trailing echoes in rods 'D' and 'E' will remain the same.

The differences mentioned above in the received maximum amplitude of echo 'a' for Al rods 'A' to 'C' using a same ultrasonic transducer are mainly due to different ratios of p/q where p and q are the diameter of the rod and transducer respectively. The causes for the extra reduction in signal levels in thinner rods may be due to that the longitudinal waves in the thinner rod are becoming flexural in nature [9,10]. In ray acoustics, this means that a transverse component will exist together with the longitudinal component of particle displacement. More waves will propagate along directions having small angles of inclination with repect to the buffer rod axis, and thus strike the rod-air boundary. This results in increased mode conversion, and a decline of the signal level of 'a'. Furthermore, the efficiency of using a longitudinal transducer to excite flexural modes in a thinner rod is less than that for exciting longitudinal modes in a larger rod.

II.B Shear Waves

Shear wave measurements were made using 12.7 mm diameter Panametrics transducers with different center frequencies. A standard shear wave couplant is used between the shear wave

transducer and the Al rod. Figures 7(a)-(d) were obtained with a 2.25 MHz transducer and rods 'A', 'B', 'C' and 'E' respectively in the reflection geometry and the amplitudes were arbitrary. The measurement with rod 'D' is given below. The frequency 2.25 MHz is chosen here because the shear wavelength is comparable to the longitudinal wavelength in the longitudinal wave measurements performed in the previous section. It is obvious that no trailing echo is observed. When the shear waves travelling nearly parallel to the rod-air interface strike the interface, the phase matching requirements indicate that they can not have the kind of mode conversion process which induces the dominant trailing pulses observed in the longitudinal wave measurements. Only a total reflection phenomenon happens at the periphery of the rod, thus a continuous trailing echo is seen.

The reflected shear wave signals from the end of rod 'E' (tapered) and rod 'B' (12.7mm dia.) are of similar level. However, the reflected signals from the rod 'D' (spiral grooves) is not only more than -40 db lower in signal level but also extremely messy. The signal reflected from the rod end can not be identified. This reduction in signal level is obviously due to the grooves, but the difference in the degree of reduction between the longitudinal and shear incident waves is large and not understood. The messy signals are due to reflections from the grooves.

In all the shear wave measurements performed on rods 'A' to 'E' with a 2.25 MHz transducer the received signal is very sensitive

to the boundary conditions. For instance hand pressure at the rod periphery will change signal levels by about 5 db. This does not appear at all in the longitudinal wave measurements. From all the results obtained it is, therefore, concluded that for the same acoustic wavelength the diameter of the Al buffer rod for shear wave propagation should be much larger than that for the longitudinal waves.

III. CONCLUSIONS

When longitudinal waves are propagated in cylindrical buffer rods, numerous "trailing echoes" are observed in addition to the first arrival echo. These trailing echoes are regularly separated in time and are associated with mode conversion at the walls of the buffer rod. It is possible to eliminate these echoes by machining grooves along the walls of the rods, or more efficiently by using conical buffer rods. The behavior with shear waves is different because mode conversion does not occur. In this case messy signals are associated with multiple reflections at the walls of the rod. Best results for shear waves are obtained with rods of relatively large diameter.

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FIGURE CAPTIONS

Fig.1 Five Al rods used in the measurements.

Fig.2 The reflected echoes through the Al Rod 'B' using a 5 MHz KB-Aerotech longitudinal transducer with a 12.7 mm diameter.

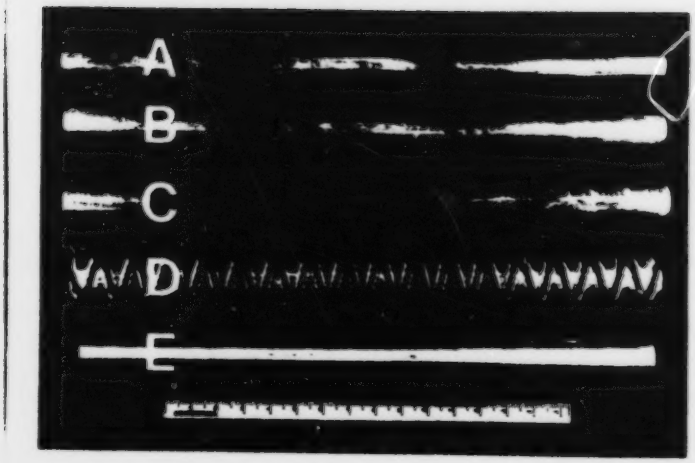
Fig.3 The received echoes 'a', 'b' and 'c' for Al rods (a) 'A' (7.95 mm dia.) (b) 'B' and (12.7 mm dia.) (c) 'C' (19 mm dia.) using the transducer described in Fig.1. The amplitudes are arbitrary.

Fig.4 (a) The phase matching requirements represented by the slowness curves for mode conversion processes which cause the trailing echoes in an isotropic material, (b) the propagation paths for echoes 'a' and 'b'.

Fig.5 The echo 'a' and the trailing echoes through the Al Rod 'D' (with double spiral notches) using the transducer decribed in Fig.1.

Fig.6 The echo 'a' and the trailing echoes through the Al Rod 'E' (tapered rod) using the transducer decribed in Fig.1.

Fig.7 The received signals reflected from the rod (a) 'A', (b) 'B', (c) 'C' and (d) 'E' (tapered) with a 2.25 MHz and 12.7 mm diameter Panametrics shear transducer.



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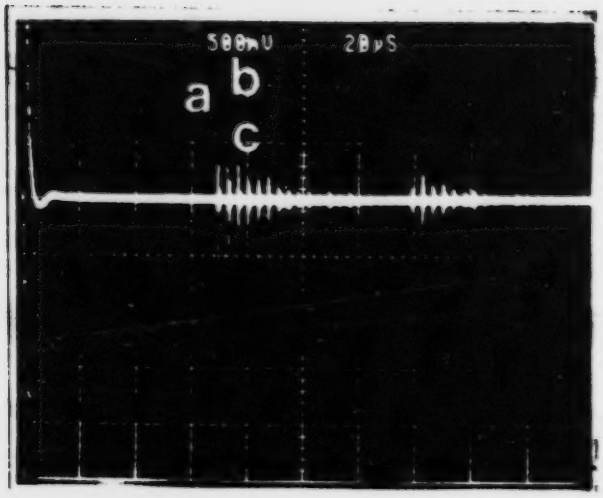


Fig.2 The reflected echoes through the Al Rod 'B' using a 5 MHz KB-Aerotech longitudinal transducer with a 12.7 mm diameter.

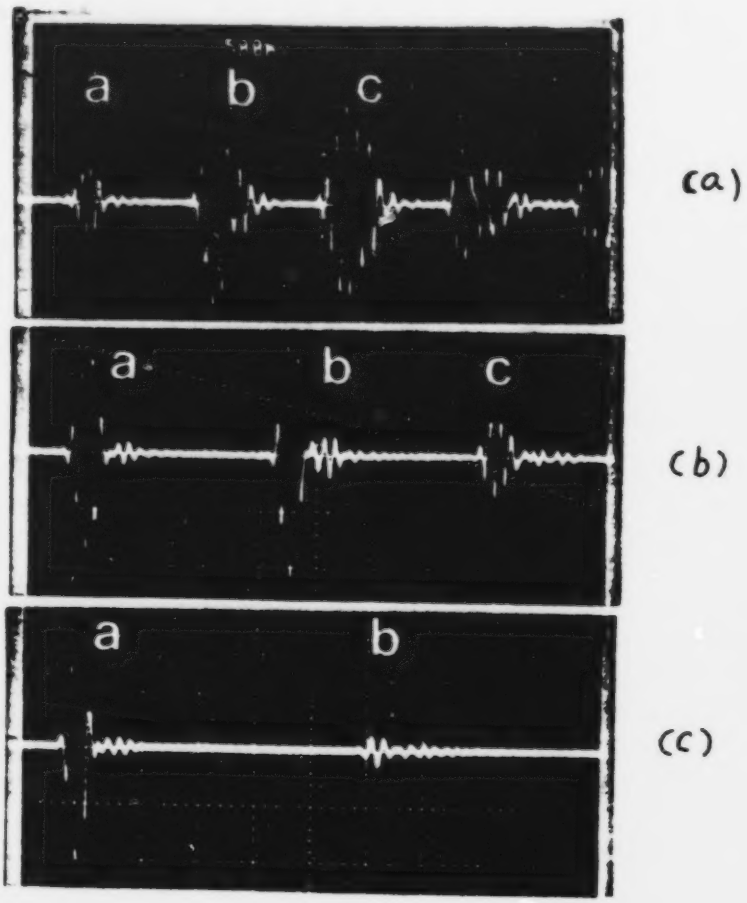
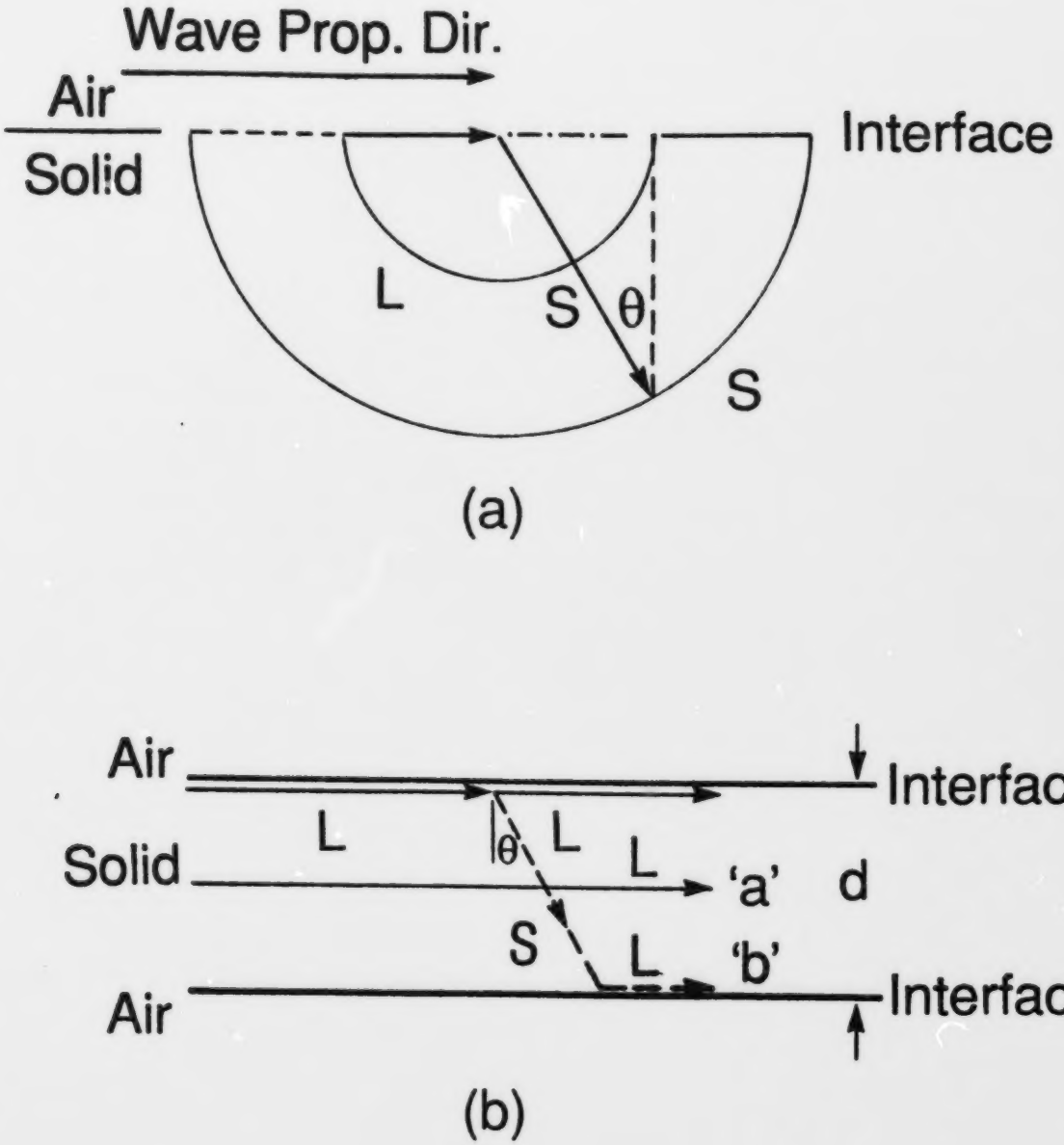


Fig.3 The received echoes 'a', 'b' and 'c' for Al rods (a) 'A' (7.95 mm dia.) (b) 'B' and (12.7 mm dia.) (c) 'C' (19 mm dia.) using the transducer described in Fig.1. The amplitudes are **arbitrary.**



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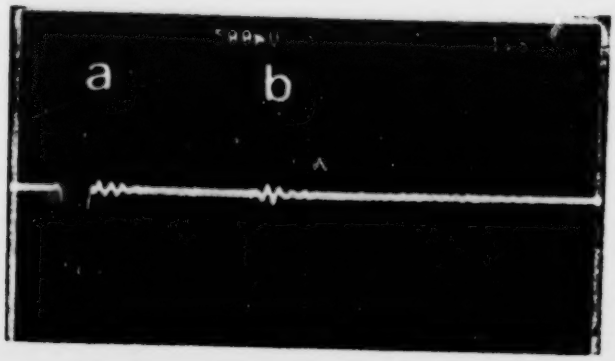

Fig.5 The echo 'a' and the trailing echoes through the Al Rod 'D' (with double spiral notches) using the transducer decribed in Fig.1.

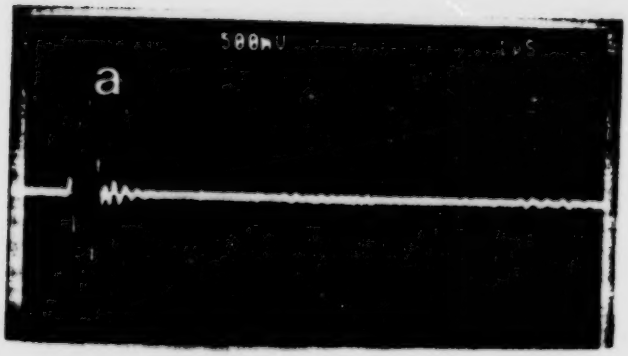

Fig.6 The echo 'a' and the trailing echoes through the Al Rod 'E' (tapered rod) using the transducer decribed in Fig.1.

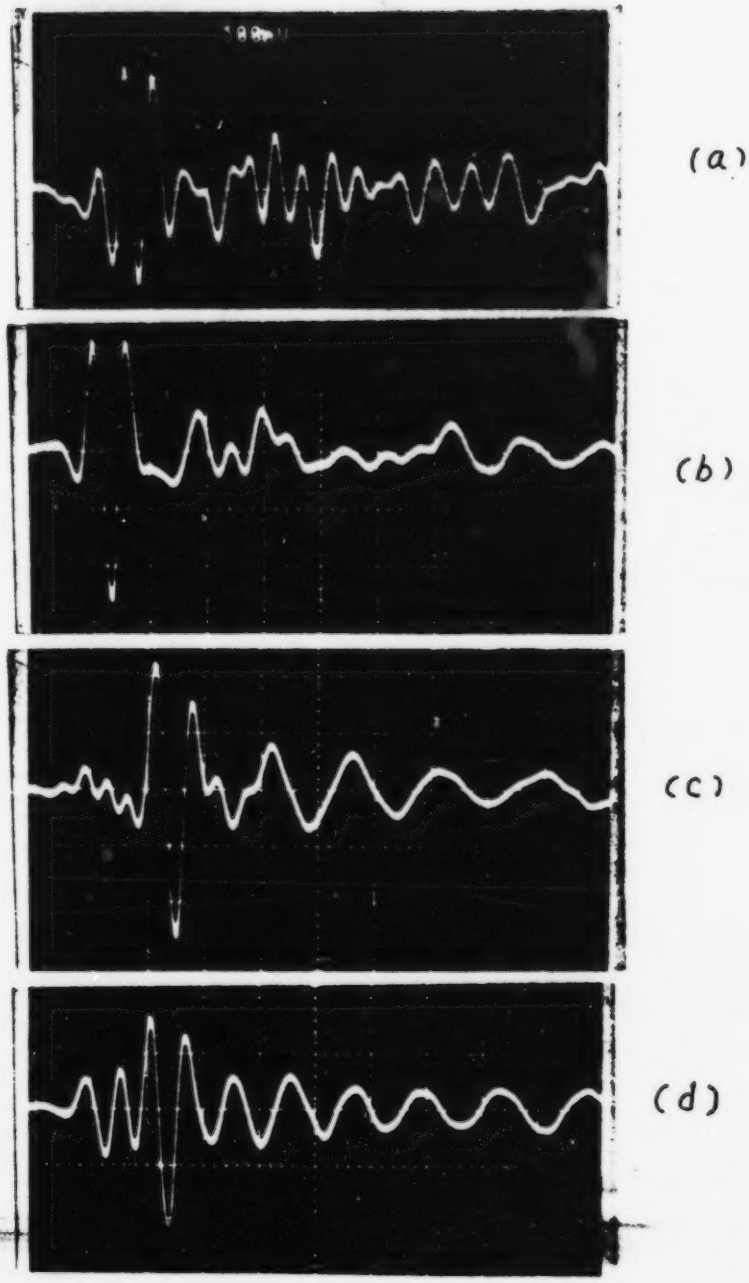

Fig.7 The received signals reflected from the rod (a) 'A', (b) 'B', (c) 'C' and (d) 'E' (tapered) with a 2.25 MHz and 12.7 mm diameter Panametrics shear transducer.